AD-A238 934

(2)

FINAL TECHNICAL REPORT

JUL 18 1991

ONR CONTRACT #N00014-87-K-0228/P00004

"Theoretical & Observational Marine Boundary Layer Studies"

Submitted to:

Office of Naval Research (ONR)
Dr. Robert F. Abbey, Jr.
Office of Naval Research, Ocean Sciences Division
Marine Meteorology Program, Code 1122MM
800 North Quincy Street
Arlington, VA (703) 696-6598

Submitted by:

Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523

Principal Investigators:

Stephen K. Cox
Professor and Department Head
(303) 491-8594

Wayne H. Schubert
Professor
(303) 491-8521

Graeme L. Stephens
Professor
(303) 491-8521

Contracts and Grants Administrator:

John E. Caron
Contracts and Grants Administrator
Office of Sponsored Programs
Colorado State University
Fort Collins, CO 80523
(303) 491-6355

DISTRIBUTION STATEMENT A
Approved for public release
Distribution Unlimited

91-05077

"Theoretical & Observational Marine Boundary Layer Studies"

The activities pursued under ONR Contract No. N00014-87-K-0228/P00005,A00001 have focused upon obtaining a more complete understanding of the physical and dynamic processes which govern marine boundary layer cloud systems. These activities have spanned the planning, deployment, execution and analysis phases of the FIRE I Marine Stratocumulus Experiment conducted during July, 1986 off the coast of southern California; the surface based component of this experiment was conducted from San Nicolas Island and the aircraft component was conducted from North Island Naval Base, San Diego, California.

In preparation for the ASTEX experiment, three of the principal investigators on this project have participated heavily in the preparation of the ARI proposal and subsequent experimental design for ASTEX.

Summaries of results of scientific investigations conducted under the auspices of this grant are given below.

Analysis of Boundary Layer Sounding Data from the FIRE Marine Stratocumulus Project:

We have conducted an analysis of the boundary layer thermodynamic data obtained by the CLASS radiosonde system during the marine boundary layer experiment on San Nicolas Island in the summer of 1987. The analysis procedure retains the highest possible vertical resolution in the data. Plots of temperature, dew point temperature, potential temperature, equivalent potential temperature and saturation equivalent potential temperature are presented for each of the sixty-nine soundings taken during FIRE. Conditions were mostly cloudy with fifty-five of the sixty-nine soundings being released with stratocumulus overhead. For the fifty-five cloudy soundings, cloud top jumps of equivalent potential temperature θ_e and total water mixing ratio r were also determined. Each of these soundings is then represented by a point in the $(\Delta\theta_e \Delta r)$ plane. Fifteen of these soundings are on the unstable side of the evaporative instability line, and there appears to be some tendency for break-up under these conditions.

Stability of Cloud-topped Boundary Layers:

According to the thermodynamic theory of cloud top evaporative instability, persistent stratocumulus should be observed only when the cloud top jumps in equivalent potential temperature θ_e and total water mixing ratio r satisfy the stability condition $\Delta\theta_e > k(L/c_p)\Delta r$, where $k \approx 0.23$. Using observations of persistent mid-latitude and subtropical stratocumulus we find that the above stability condition is violated in many cases. In an attempt to understand how stratocumulus can persist under apparently unstable conditions we first review the thermodynamic instability theory and then develop a dynamical framework using a two-dimensional Boussinesq moist convection model with spectral

A-1

discretization and with resolution sufficient to simulate cloud top processes. Idealized initial value experiments confirm that, when the above condition is violated, evaporative instability leads to cloud breakup through sequential dissections of existing cloud. However, initial conditions close to the critical stability line (e.g. $\Delta\theta_e$, $(L/c_p)\Delta r$ = *-6K, -15K)* lead to cloud breakup with a characteristic cloud half-life of several hours, while physically realistic initial conditions far from the critical stability line (e.g. $\Delta\theta_e$, $(L/c_p)\Delta r$ = *-16K, -25K)* lead to more rapid breakup, with a cloud half-life on the order of 1/2 hour. When evaporative instability is so weak that the associated cloud half-life is as long as several hours, other physical processes (such as surface evaporation) can apparently moisten the boundary layer rapidly enough to mask the cloud breakup process.

On the Cloud Absorption Anomaly:

We have provided an overview of the subject of absorption of solar radiation by water clouds in the earth's atmosphere. The paper summarizes the available evidence which points to disagreements between theoretical and observed values of both cloud absorption and reflection. The importance of these discrepancies, particularly to remote sensing of clouds as well as to studies of cloud physics and earth radiation budgets, is emphasized. Existing cloud absorption and reflection measurements are reviewed and the persistent differences that exist between calculated and measured near-infrared cloud albedos are highlighted. Various explanations for these reflection and absorption discrepancies are discussed and a simple outline of the theory of cloud absorption is provided. This outline is used to examine the large-droplet hypothesis as well as the effects of absorbing aerosol and enhanced water vapor continuum absorption. A further hypothesis regarding the effects of cloud inhomogeneities is also examined. While the theory of cloud absorption is not completely understood, especially with regard to inhomogeneous clouds, the underlying conclusion of this paper points to the need for better measurements of solar radiation in clouds, water vapor absorption and microphysics properties of clouds.

A Modelling Study of the Cloud-topped Marine Boundary Layer:

A coupled convective-radiative, boundary-layer model of marine stratocumulus clouds has been developed and presented as a user-friendly research investigation tool. The model, which slightly generalizes Lilly's (1968) cloud-topped mixed-layer model, has as dependent variables the cloud-top height, the cloud-base height, mixed-layer equivalent potential temperature and total water mixing ratio, the turbulent fluxes of equivalent potential temperature, total water mixing ratio, and virtual potential temperature, the cloud-top jumps of equivalent potential temperature and total water mixing ratio, the cloud-top temperature, and the net radiative flux divergence at cloud top and in the mixed layer.

The model has been programmed for both the steady-state and time dependent cases using two different closure assumptions. Closure method one is a weighted average of Lilly's (1968) maximum and minimum entrainment assumptions. Closure method two assumes the ratio of the integral buoyant energy dissipation to the buoyant energy production to

be constant. Experiments were performed to determine which closure method produced the best results, and to simulate the observed diurnal thinning of the marine stratocumulus clouds.

Results indicate that closure method two provides a more realistic representation of the observed marine boundary layer than does closure method one for both the steady-state case and the time dependent case. Results from the diurnal cycle simulations indicate that it is possible to simulate the observed thinning trend of the stratocumulus cloud layer although the magnitude of the thinning is less than observed. Results also indicate that think clouds are more susceptible to thinning than are thick clouds.

Cloud Field Reflectance Variations Traceable to Finite Cloud Effects:

Results of experiments conducted using the Cloud Field Optical Simulator (CFOS) to examine the variability in reflectance properties of cloud fields with fixed cloud amount but different cloud patterns have been analyzed and reported. Angular reflectance data from 20 cloud fields with a common cloud amount of 30 percent were analyzed. The experiment demonstrated the problem of changing spot size as a function of view angle for a fixed field of view detector.

Seven different incident solar zenith angles were analyzed for variations in reflected irradiances arising from different cloud field patterns. Results show irradiance variations as great as 31% at large incident zenith angles. Also indicated are increased irradiances and increased anisotropy at large incident zenith angles.

Radiances and irradiances of interacting cloud elements were compared to those of noninteracting clouds. Interacting cloud fields produced larger radiance and irradiance values than noninteracting cloud fields. The differences between interacting and noninteracting cloud fields were greater at smaller source zenith angles. Maximum radiances were found at photodiode locations measuring backscattered radiation in the interacting cloud fields.

Reflectances were integrated as a function of zenith angle to produce daily reflectances for five different latitude/date combinations. Analysis of this study demonstrated the importance of the sides of clouds, and verified irradiance differences due to cloud patterns when examined on a daily scale.

Irradiances calculated utilizing 195 radiances, each measured at different local zenith and azimuth angles, were compared with irradiances calculated from a single radiance assuming isotropy. The isotropic assumption produced overestimates of the measured irradiances at large local zenith angles when the photodiode detectors measured backscattered radiation, and underestimates when the detectors measured forward scattered radiation. Minimum errors were found at small local zenith angles.

Microphysical and Radiative Properties of Marine Stratocumulus from Tethered Balloon Measurements:

Vertical profiles of cloud microphysical data and longwave and shortwave radiation measurements through the marine boundary layer were obtained using an instrument package on the NASA tethered balloon during the FIRE Marine Stratocumulus Experiment. The radiation observations were analyzed to determine heating rates inside the stratocumulus clouds during several tethered balloon flights. The radiation fields in the cloud layer were also simulated by a two-stream radiative transfer model, which used cloud optical properties derived from microphysical measurements and Mie scattering theory.

The vertical profiles of the observed longwave cooling rates were similar in structure and magnitude not only to previous measurements of marine stratocumulus, but also to the cooling rates computed by the two-stream radiative transfer model. The solar heating rates measured in the clouds, however, were systematically much larger than the rates calculated in the model.

Solar albedo measurements showed that the visible spectrum tended to be reflected by the clouds more than the near IR spectrum. This is similar to the results reported by Hignett, although the discrepancies between the observed and calculated near IR to visible albedo ratios were generally much smaller. The results from the flights on 10 and 13 July 1987, however, suggest that the effects of heterogeneities on the radiative transfer through the cloud may be more important in the visible than in the near IR.

Students Supported by ONR Project N00014-87-K-0228/P00004

Steven Ackerman
Graduated: 1987, Ph.D
Thesis Title: *Radiative Characteristics of Soil Derived Aerosols*

Timothy Alberta
Graduated: 1987, MS
Thesis Title: *Anisotropy in Reflected Solar Radiation from Fields of Finite Clouds*

Cynthia Combs
Graduated: 1988, MS
Thesis Title: *Transmittance of Solar Radiation Determined by the Multiple Field of View Radiometer under Various Cloud Covers for Mauna Loa, Hawaii*

David Duda
Graduated: 1989, MS
Thesis Title: *Microphysical and Radiative Properties of Marine Stratocumulus from Tethered Balloon Measurements.*

William Smith, Jr.
Graduated: 1989, MS
Thesis Title: *The Broadband Radiative Properties of Cirrus Clouds Deduced from Aircraft Measurements During FIRE*

Paul Stackhouse
Graduated: 1989, MS
Thesis Title: *A Theoretical and Observational Comparison of Cirrus Cloud Radiative Properties.*

John Withrow
Graduated: 1992, MS
Thesis Title:

David Duda
Graduated: 1993, Ph.D.
Thesis Title:

List of Publications
ONR Project N0O014-87-K-0228/P0O0O4

Schubert, W. H., P. E. Ciesielski, T. B. McKee, J. D. Kleist, S. K. Cox, C. M. Johnson-Pasqua and W. L. Smith, Jr., 1987: Analysis of boundary layer sounding data from the FIRE marine stratocumulus project: FIRE volume 2. Atmospheric Science Paper No. #419, 101 pp., Colorado State University, Department of Atmospheric Science, Fort Collins, CO 80523.

Smith, W. L., Jr., S. K. Cox and V. Glover, 1988: Temperature sensitivity of Eppley broadband radiometers. FIRE Series No. 5, Atmospheric Science Paper No. 423, 12 pp. Colorado State University, Department of Atmospheric Science, Fort Collins, CO 80523.

Kuo, H.-C., and W. H. Schubert, 1988: Stability of cloud-topped boundary layers. *Quart. J. Roy. Meteorol. Soc.*, 114, 887-916.

Ackerman, S. A. and S. K. Cox, 1988: Shortwave radiative parameterization of large atmospheric aerosols: dust and water clouds. *J. of Geophysical Res.*, 93, 11,063-11,073.

Alberta, T. L. and S. K. Cox, 1989: Variations in cloud field reflectance arising from finite cloud effects. Book Entitled: IRS '88: Current Problems in Atmospheric Radiation, Editors: J. Lenoble & J-F. Geleyn, Published by, A. Deepak Publishing, Hampton, VA. pg. 68.

Duda, D. P., and G. L. Stephens, 1989: Microphysical and radiative properties of marine stratocumulus from tethered balloon measurements. Atmospheric Science Paper No. 453, ISSN Series #0067-0340, Colorado State University, Fort Collins, CO 80523, 123 pp.

Hein, P. F., et al., 1989: The CSU tethered balloon data set of the FIRE marine stratocumulus IFO. FIRE Series No. 6, Atmospheric Science Paper No. 432, ISSN Series #0067-0340, Colorado State University, Fort Collins, CO 80523, 33 pp.

Olsson, P. and S. K. Cox, 1989: Inference of horizontal temperature gradients using passive radiometric methods. Atmospheric Science Paper No. 447, ISSN Series #0067-0340, Colorado State University, Fort Collins, CO 80523, 59 pp.

Smith, W. L., Jr., 1989: The broadband radiative properties of cirrus clouds deduced from aircraft measurements during FIRE. FIRE Series No. 7, Atmospheric Science Paper No. 448, ISSN #0067-0340 Colorado State University, Fort Collins, CO 80523, 65 pp.

Stackhouse, P. W., Jr. and G. L. Stephens, 1989: A theoretical and observational comparison of cirrus cloud radiative properties. Colorado State University, Department of Atmospheric Science, Blue Book No. 452.

Stephens, G. L. and S-C Tsay, 1990: On the cloud absorption anomaly to appear: *Quart. J. Roy. Meteor. Soc.*, 116, 671-704.

Stephens, G. L. and P. Gabriel and S-C Tsay, 1991: Statistical radiative transport in one-dimensional media and its application to the terrestrial atmosphere. *Trans. Theory and Stat. Phys.*, 20.

Guinn, T. A., 1989: A modeling study of the cloud-topped marine boundary layer. Atmospheric Science Paper No. 458, Colorado State University, Fort Collins, CO 80523, 63 pp.

Alberta, T. L. and S. K. Cox, 1990: Cloud field reflectance variations traceable to finite cloud effects. *J. Appl. Meteor.*, 29, 165-178.

Duda, D. P., and G. L. Stephens, 1991: Microphysical and radiative properties of marine stratocumulus from tethered balloon measurements. *J. of Appl. Meteor.*, 30, 170-186.

List of Conference Proceedings
ONR Project N00014-87-K-0228/P00004

FIRE Conference, Vail, CO, July 1988:

Smith, W. L., Jr., S. K. Cox and V. Glover: Temperature sensitivity of Eppley Broadband Radiometers.

Schubert, W. H., P. E. Ciesielski, T. A. Guinn, S. K. Cox and T. B. McKee: Analysis of Tethered Balloon, Ceilometer and Class Sounding Data taken on San Nicholas Island during the FIRE Project.

Hein, P., W. L. Smith, Jr., and S. K. Cox: Radiative Properties of Cirrus Clouds. FIRE IFO Case 10/28/86.

Cox, S. K., D. P. Duda, T. A. Guinn, C. M. Johnson-Pasqua, W. H. Schubert and J. B. Snider: Analysis of tethered balloon data from San Nicholas Island on 8 July 1987.

International Radiation Symposium, Lille, France, August, 1988:

Cox, S. K.: Cloud and Radiation Field Experiments of the 1980's. Invited presentation.

Alberta, T. L. and S. K. Cox: Variations in Cloud Field Reflectance Arising from Finite Cloud Effects.

FIRE Conference, Monterey, CA, July 1989:

Albrecht, B. A., C. W. Fairall, W. Syrett, W. H. Schubert and J. B. Snider: Cloud and boundary layer structure over San Nicholas Island during FIRE.

Duda, D. P., G. L. Stephens and S. K. Cox: The radiation budget of stratocumulus clouds measured by tethered balloon instrumentation: Variability of flux measurements.

Hein, P. G. and S. K. Cox: Spatial scales of cirrus cloud properties.

Smith W. L., Jr. and S. K. Cox: Radiative properties of cirrus clouds inferred from broadband measurements during FIRE.

Stephens, G. L.: Cirrus clouds and climate feedback: Is the sky falling and should we go tell the King? (This is not published in the proceedings but was presented at the meeting.)

Stephens, G. L., P. J. Flatau, S-C Tsay and P. Hein: Radiative diffusivity factors in cirrus and stratocumulus clouds - Applications to two stream models.